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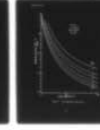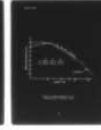F/G 17/5

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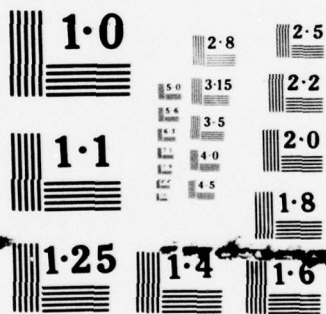UNCLASSIFIED

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2.8 MICRON INFRARED HETERODYNE RADIOMETER

AIL, Div. of Cutler-Hammer
Deer Park, Long Island, NY 11729

January 1978

Final Report

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AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117

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This report has been reviewed by the Office of Information (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

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TERRENCE F. DEATON
Capt, USAF
Project Officer

JAMES D. DILLOW
Lt Col, USAF
Chief, Advanced Beam Control Branch

FOR THE COMMANDER

ARMAND D. MAIO
Lt Col, USAF
Chief, Advanced Laser Technology Division

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A gain modulated, Dicke switched Infrared Heterodyne Radiometer (IHR) has been designed, developed, and tested which is capable of measuring the atmospheric absorption characteristics within a 200 MHz bandwidth about selected hyrdogen fluoride (HF) laser transistions between 2.7 and 3.1 micrometers.

The IHR has been installed in a KC-135 test aircraft. Provisions for remote control and remote calibration were incorporated into the radiometer.

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The heterodyne receiver sensitivity (NEP) of the IHR is 1.3×10^{-19} W/Hz and the calculated temperature resolution $(\Delta T_S/T_S)$ is given for a variety of source temperatures and total transmittances (α).

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SECTION I

INTRODUCTION

The objective of this program was the design, development and construction of a gain modulated, Dicke switched Infrared Heterodyne Radiometer (IHR) which is suitable for the measurement of the atmospheric absorption characteristics at the hydrogen fluoride (HF) laser wavelengths.

The vertical path atmospheric transmission at selected CO_2 laser transitions have been reported for ground-based (ref. 1 to 3) and airborne (ref. 4) infrared heterodyne radiometers. Ground-based IHR measurements at HF and DF laser transitions have also been reported (ref. 5). An IHR has been developed and tested which is designed for use as an airborne platform and is capable of measuring received solar radiation within a 200 MHz bandwidth about selected HF laser transitions.

The solar flux will be measured at several laser wavelengths between 2.7 and 3.1 microns using the IHR. These data will then be used to derive the absorption coefficients at various altitudes in the atmosphere for each of these laser wavelengths. During the development of the IHR, consideration was also given to the feasibility of airborne operation with the DF and the CO lasers at 3.8 and 5.0 μm, respectively.

The IHR optical package (figure 1) has been designed for remote operation because of the limited instrument accessibility
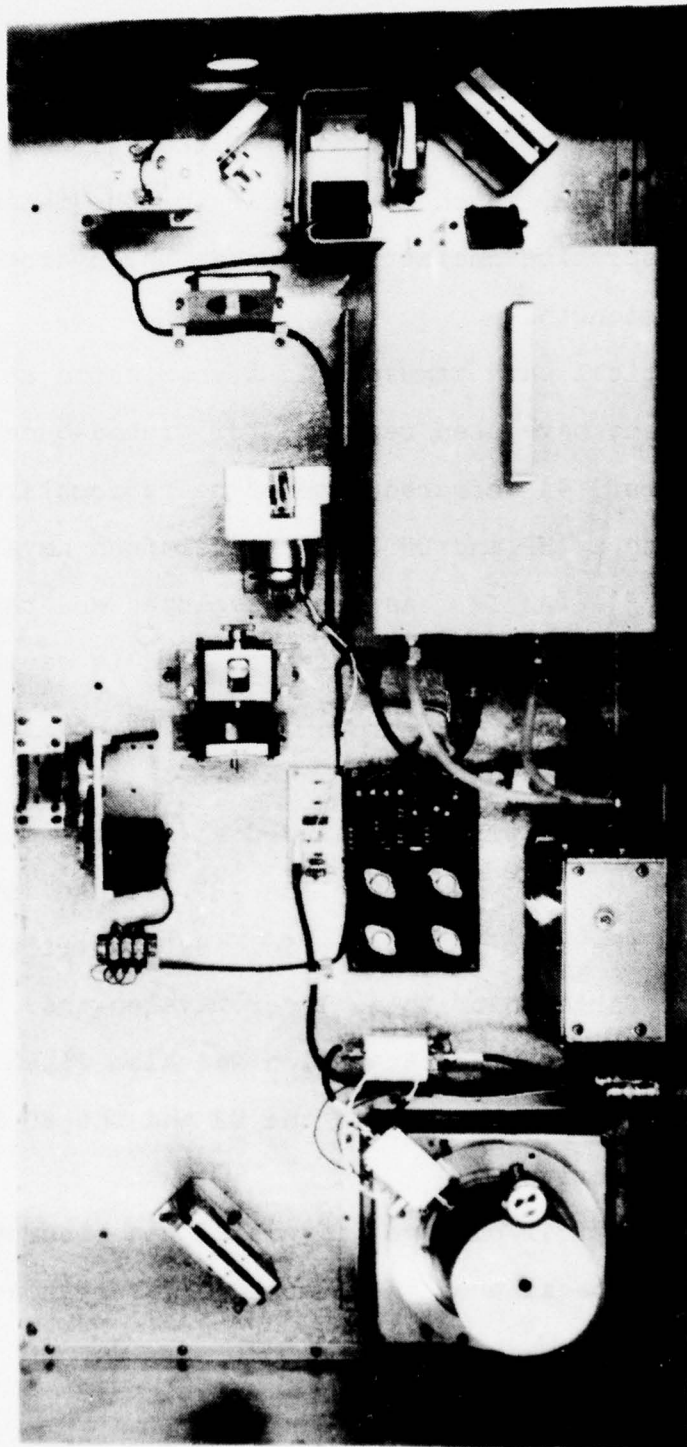
Figure 1. Top View of the 2.8 Micron Infrared Heterodyne Receiver Unit.

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which is available when the instrument is mounted in a KC-135
military aircraft. A ruggedized cryogenic dewar, an RFI inter-
connection network, a remotely controlled calibration network
and a processing radiometer with an analog/digital output has
been incorporated into the IHR.

SECTION II

INFRARED HETERODYNE RADIOMETERS

General: A Dicke-switched IHR using IF gain modulation was designed,
developed and fabricated. The IHR package includes: (1) a photo-
voltaic InSb infrared mixer element, (2) a diffraction limited
infrared collection system, (3) an infrared Dicke switch, (4) a
calibration subsystem which uses a 1900 K blackbody source, and
(5) a radiometric processing back-end.

Using the IHR, high resolution infrared radiometric measure-
ments can be carried out that are unachievable using conventional
direct detection techniques. The predetection electronic (IF)
bandwidth of 100 MHz establishes the instantaneous infrared band-
width of the IHR (6.7×10^{-3} cm^{-1}) and still finer spectral resolu-
tion is achievable by using narrower IF filters.* The IHR spectral
resolution is two to three orders of magnitude finer than is pres-
ently obtainable with conventional spectroscopic techniques and
permits evaluation of fine grain structure of thermal emission-
absorption spectra. In addition, infrared vibration-rotation
signature lines which overlap the laser local oscillator transi-
tion can be remotely examined.

The basic arrangement of the IHR instrument, shown in figure 2,
includes optics for the collection of solar radiation, a Dicke switch,
optical elements for relaying the infrared radiation to a photomixer,

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*The IHR specificity will be ultimately limited by the frequency
stability of the laser LO.

SOLAR RADIATION

COLLECTING
OPTICS

CALIBRATION
BLACKBODY

DICKE SWITCH

IR OPTICS
AND DETECTOR

PREAMPLIFIER
POSTAMPLIFIER

IF FILTER (B)

SQUARE LAW
DETECTOR

SWITCH GENERATOR
(F_M)

VIDEO
AMPLIFIER

B = IF BANDWIDTH
F_M = SWITCH FREQUENCY
τ = INTEGRATION TIME

SYNCHRONOUS
DETECTOR
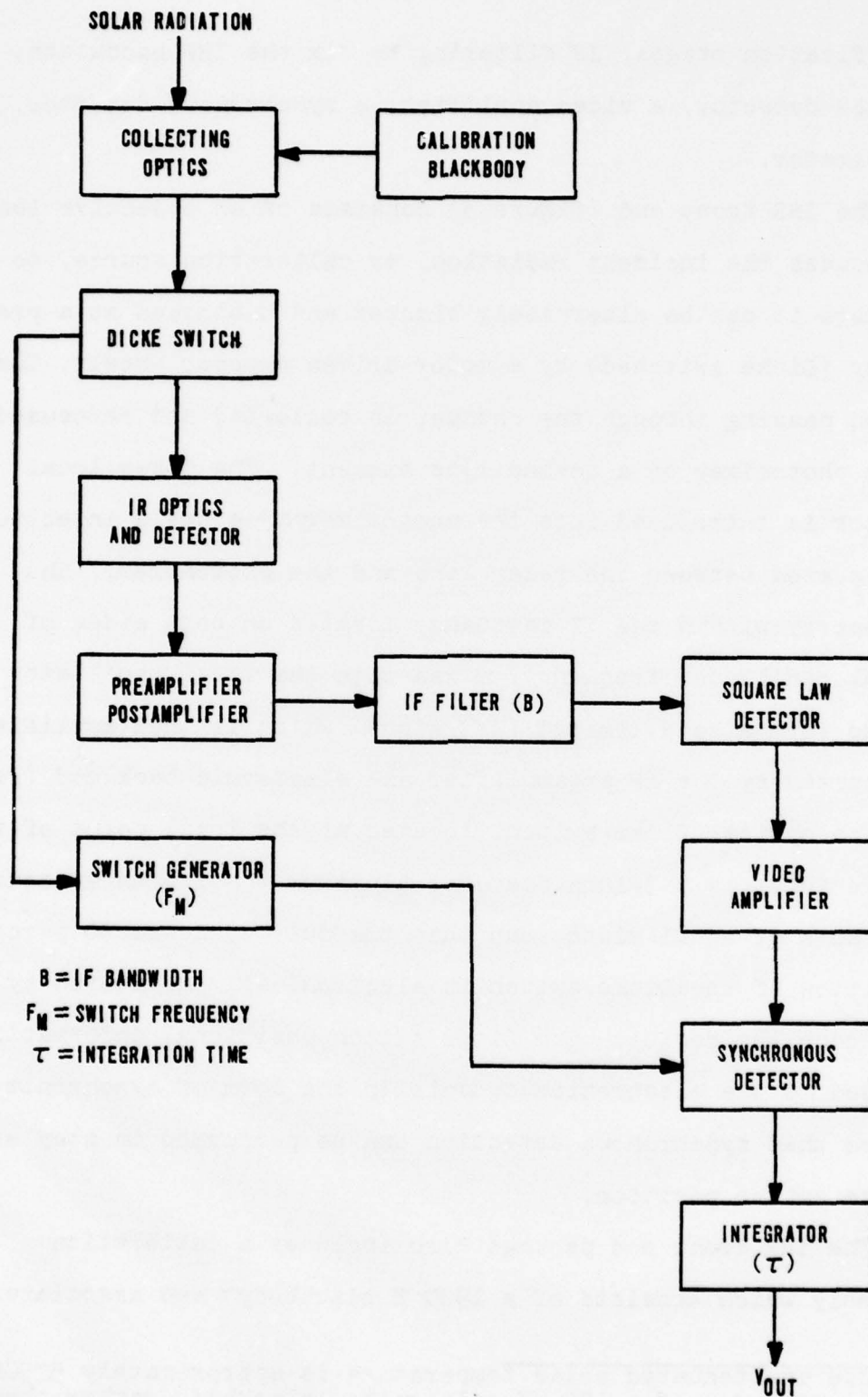
INTEGRATOR
(τ)

V_{OUT}

Figure 2.   Block Diagram of Infrared Heterodyne Radiometer

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IF amplification stages, IF filtering to fix the IHR bandwidth, a
square law detector, a video amplifier, a synchronous detector,
and integrator.

The IHR front end (figure 3) consists of an objective lens
which focuses the incident radiation, or calibration source, to a
plane where it can be alternately blocked and unblocked at a preset
frequency (Dicke switched) by a motor driven chopper wheel. The
radiation passing through the chopper is collected and refocused
onto the photomixer by a second lens element. The laser local
oscillator is introduced into the photomixer by a small injection
mirror located between the relay lens and the photomixer. The
source energy within the IF passband, located on both sides of
the local oscillator frequency, mixes with the local oscillator
energy to form a band limited (IF) signal which is then amplified
and processed by the IF preamplifier and electronic back-end (ref. 1).

The optical Dicke switch, located at the focal point of the
objective lens, is a 3-inch diameter aluminum wheel with 20 equally
spaced slots of equal width such that the duty cycle is 50 percent.
The position of the Dicke switch is electronically monitored by an
optical coupling device. The Dicke switch positional information
is relayed to the electronics console in the form of synchronizing
pulses so that synchronous detection can be performed in step with
the Dicke switch position.

The IHR front end package also includes a calibration
subassembly which consists of a 1900 K blackbody* and associated

*Since the unattenuated solar temperature is approximately 5750K
 (ref. 6), the use of a 1900 K calibration blackbody rather than
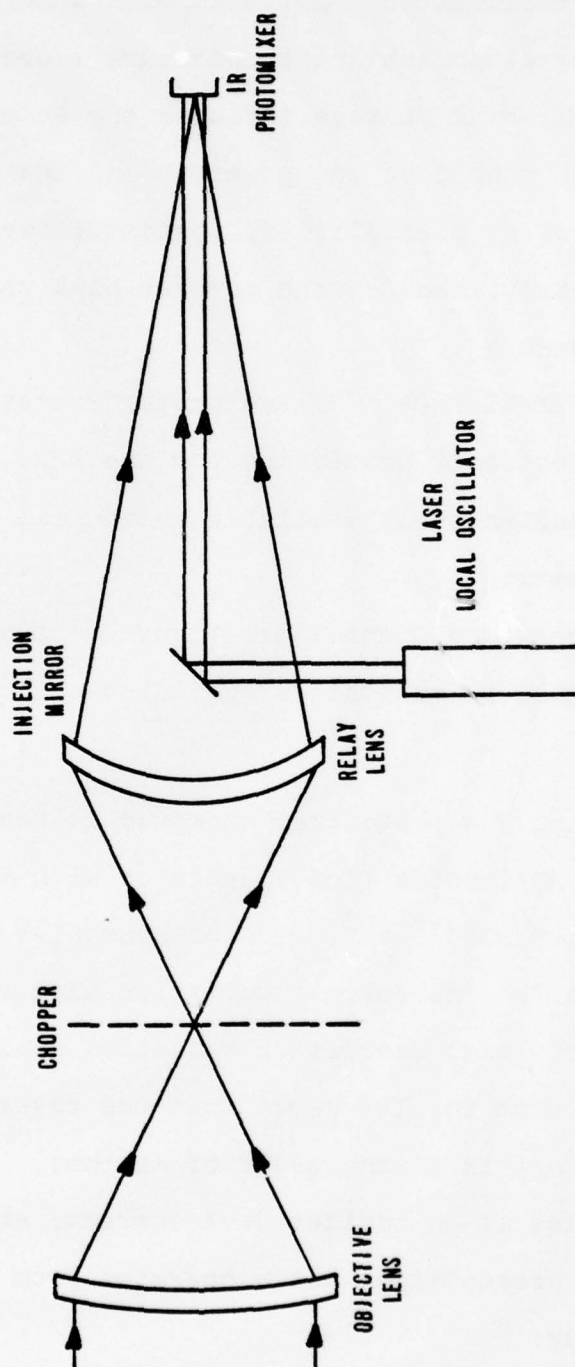 a lower temperature source will permit improved IHR resolution.

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Figure 3. Simplified Schematic of IHR Optical Train

optics. The configuration of the radiometer allows the operator
to replace the collimiated input beam with a matched beam from the
1900 K blackbody as an ambient temperature source.

The electronics package includes the Heterodyne Radiometer
Controller which supplies: (a) power to all the motorized components,
(b) ± 15 volts to the preamplifier, postamplifier and synchronous
detection circuitry, and (c) the reverse bias voltage for the
photomixer (figure 4).

The Universal Model 777 Radiometer Processor (figure 5)
provides the electronic processing for the IHR. The processor
outputs are simultaneously available in decimal (LED), binary,
and analog formats.

The Temperature Controller (figure 6) supplies the power
and control signal to maintain a specified calibration blackbody
temperature.

InSb Photomixer: The photomixer employed in the IHR is a photo-
voltaic Indium Antimonide (InSb) detector with an active area of
approximately 1.5×10^{-4} cm^2. The measured I-V characteristic is
shown in figure 7. The current variation with voltage is shown
with and without local oscillator radiation applied to the diode.
It is observed from the I-V curve that the reverse shunt resistance
for InSb detectors is of the order of megohms. This feature results
in (a) low values of photomixer dark current, and (b) the require-
ment for an IF preamplifier which operates from a relatively large
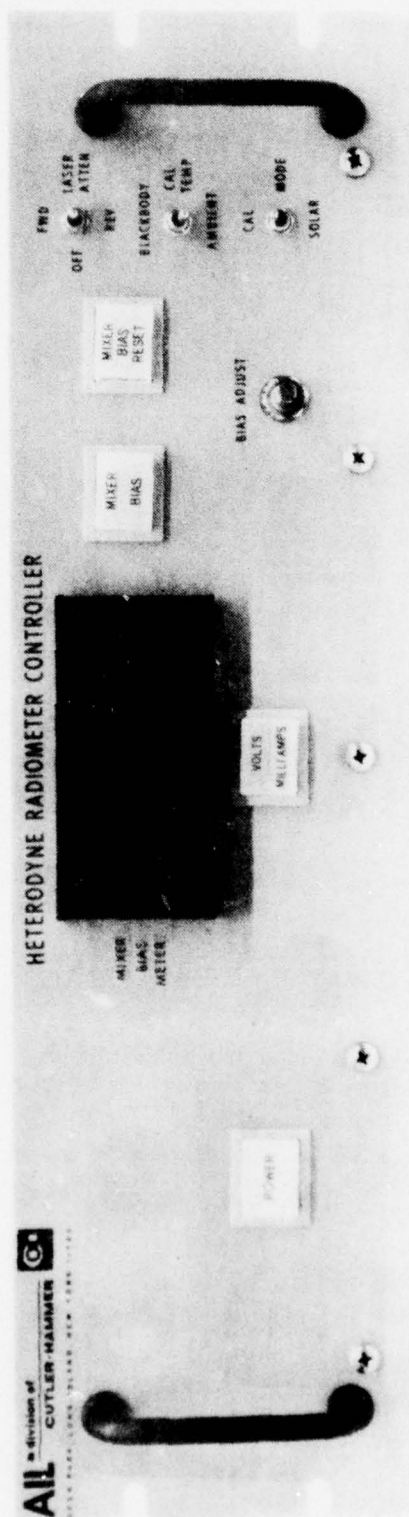source impedance.

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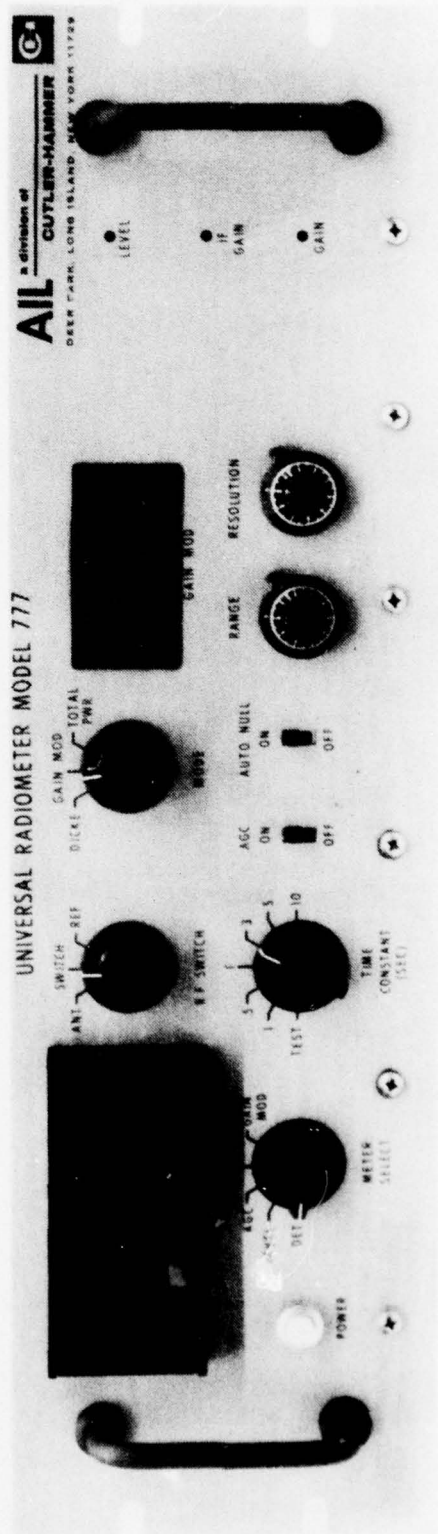Figure 4. Heterodyne Radiometer Controller Unit
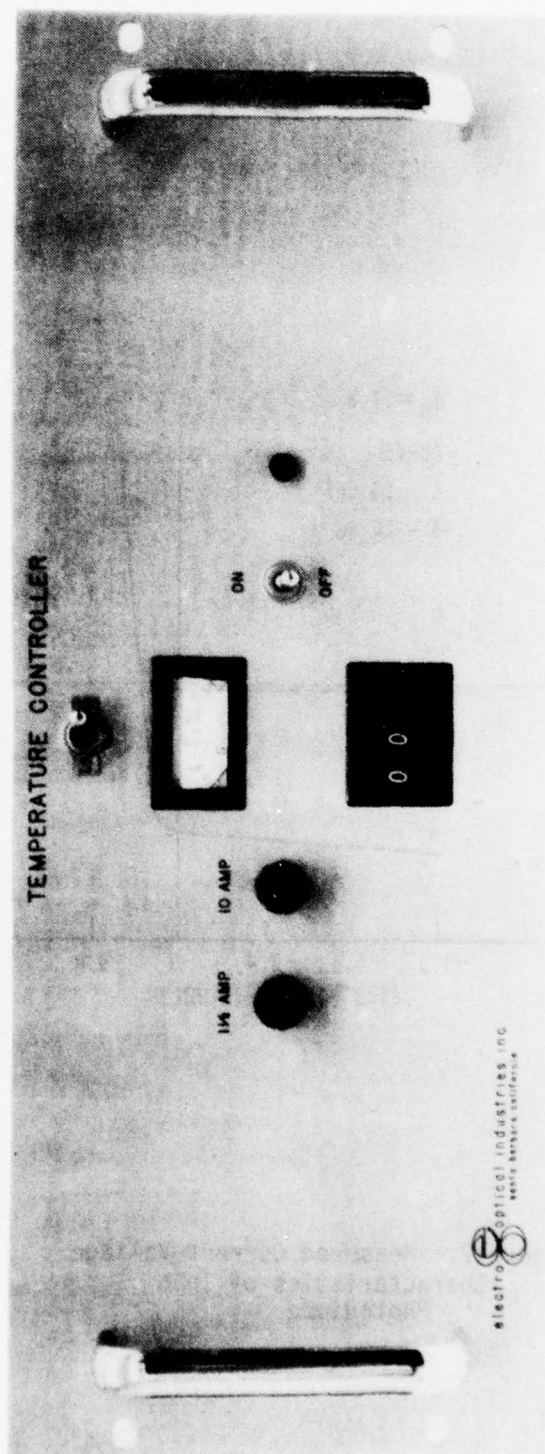
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Figure 5. AIL Universal Radiometer Unit
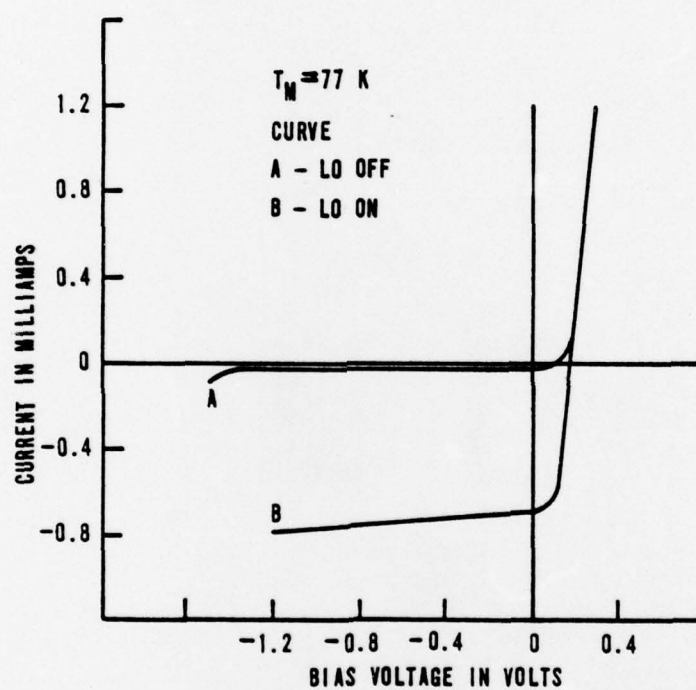
Figure 6. Temperature Controller Unit

Figure 7. Measured Current-Voltage
Characteristics of InSb
Photodiode

Frequency response measurements were carried out for the InSb photomixer, preamplifier and postamplifier combination. The measurement results are represented by a plot of the normalized heterodyne receiver response as a function of the IF frequency and is shown in figure 8 (ref. 7). It can be seen that the response of the system is down by 3 dB from its peak at a frequency of 50 MHz, for a reverse bias voltage of 600 mV, and increases to 60 MHz when the reverse bias is increased to 800 mW.

The above measurements were performed for the case of the photomixer operating at 77 K.

IHR Performance Characteristics: The IHR exhibits the following system characteristics:

Wavelength	2.7 to 3.3 μm
Receiver Type	Gain modulated, Dicke-switched heterodyne receiver
Receiver Field of View	2 mrad
Detector Sensitivity, NEP	$< 2 \times 10^{-19}$ W/Hz
Dicke Switch Rate	500 to 2000 Hz, selectable
IF Bandwidth	50 or 100 MHz, selectable
Integration Time	0.1, 0.5, 1, 3, or 10 seconds, selectable
Reference Temperature	Ambient temperature
Calibration Temperature	1000 to 1900 K, or ambient temperature
Blackbody Calibration Accuracy	$\pm$ 1 percent

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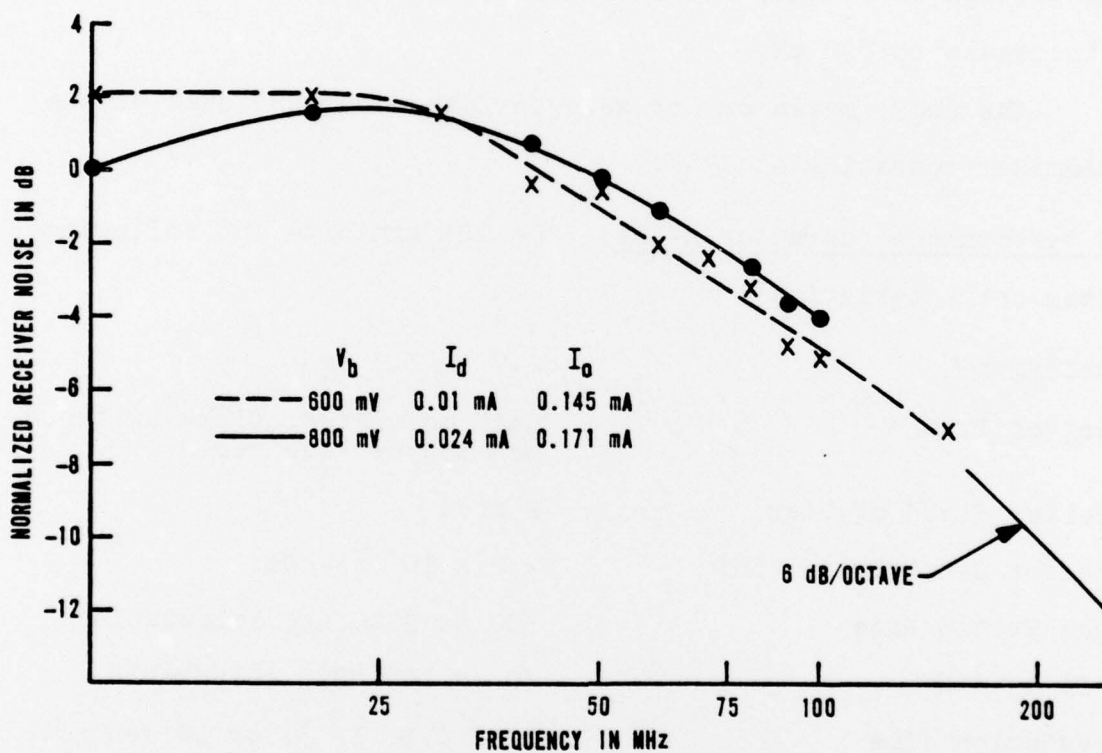
Figure 8. Measured Response of InSb
Photomixer and IF Amplifier Units

Blackbody Calibration Stability   ± 0.25 percent
        (long term)

Blackbody Calibration Stability   ± 0.05 percent
        (short term)

<u>IHR Temperature Resolution Accuracy</u>: The IHR temperature resolution ΔT_s is defined as the maximum change in source temperature for which no change in output signal-to-noise ratio is observable. The temperature resolution of the IHR is given (ref. 1) by:

$$\Delta T_s = \frac{k^2 T_s^2}{h^2 \nu^2} \cdot \left[\frac{\exp(h\nu/kT_s) - 1}{\alpha \exp(h\nu/kT_s)}\right]^2 \cdot \frac{K}{\sqrt{B\tau}} \left[k\left[\exp(h\nu/kT_s) - 1\right] + \int_{f_1}^{f_2} \frac{NEP(f)df}{kB}\right]$$

(1)

where:

α = transmittance of the media and optics between thermal source and infrared photomixer

K = sensitivity constant = 2 for Dicke-type receiver

T_s = source temperature

B = predetection bandwidth

τ = postdetection integration time for a pure integrator

ν = infrared frequency

NEP = sensitivity of heterodyne receiver

k = Boltzmann's constant

h = Planck's constant

f = IF frequency

The receiver sensitivity (NEP) for a heterodyne receiver having a photovoltaic photomixer is given (ref. 7) by:

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$$\text{NEP} \int_{f_1}^{f_2} \text{NEP}(f) df \tag{2}$$

where:

$$\text{NEP}(f) = \frac{h\nu}{\eta} \left\{ 1 + 2K \frac{(T_m + T'_{IF})}{q\ I_o} G_D \left[1 + (f/f_c)^2 \right] \right\}$$

and: η = photomixer quantum efficiency

T_m = photomixer temperature

T'_{IF} = effective input noise temperature of the IF amplifier

G_D = reverse shunt conductance of the photomixer

I_o = LO induced photocurrent

f_c = 3-dB cutoff frequency of the photomixer

The temperature resolution of the IHR is affected by optic losses, spherical aberration, coma, astigmatism, lens emissivity, lens temperature, amplitude fluctuations which occur faster than the Dicke switch rate, and the obscuration due to the LO injection mirror.

The calculated temperature resolution accuracy, $\Delta T_s/T_s$, of a gain modulated Dicke-switched IHR is given in figure 9 for $\lambda = 3$ μm, $B\tau = 5 \times 10^9$, and a heterodyne receiver NEP of 1.3×10^{-19} W/Hz with the transmittance, α, as a parameter. For a source temperature of 2000 K and a total transmittance of $\alpha = 10$ percent, the calculated temperature resolution accuracy is $\Delta T_s/T_s = 6 \times 10^{-2}$, while for $\alpha = 100$ percent the resolution accuracy improves to $\Delta T_s/T_s = 6 \times 10^{-3}$. For the solar viewing case ($T_s \approx 5750$ K) and $\alpha \approx 0.25$, the calculated temperature resolution accuracy is $\Delta T_s/T_s = 9 \times 10^{-5}$.

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$\lambda = 3.39$
$B = 1.00E\ 08$
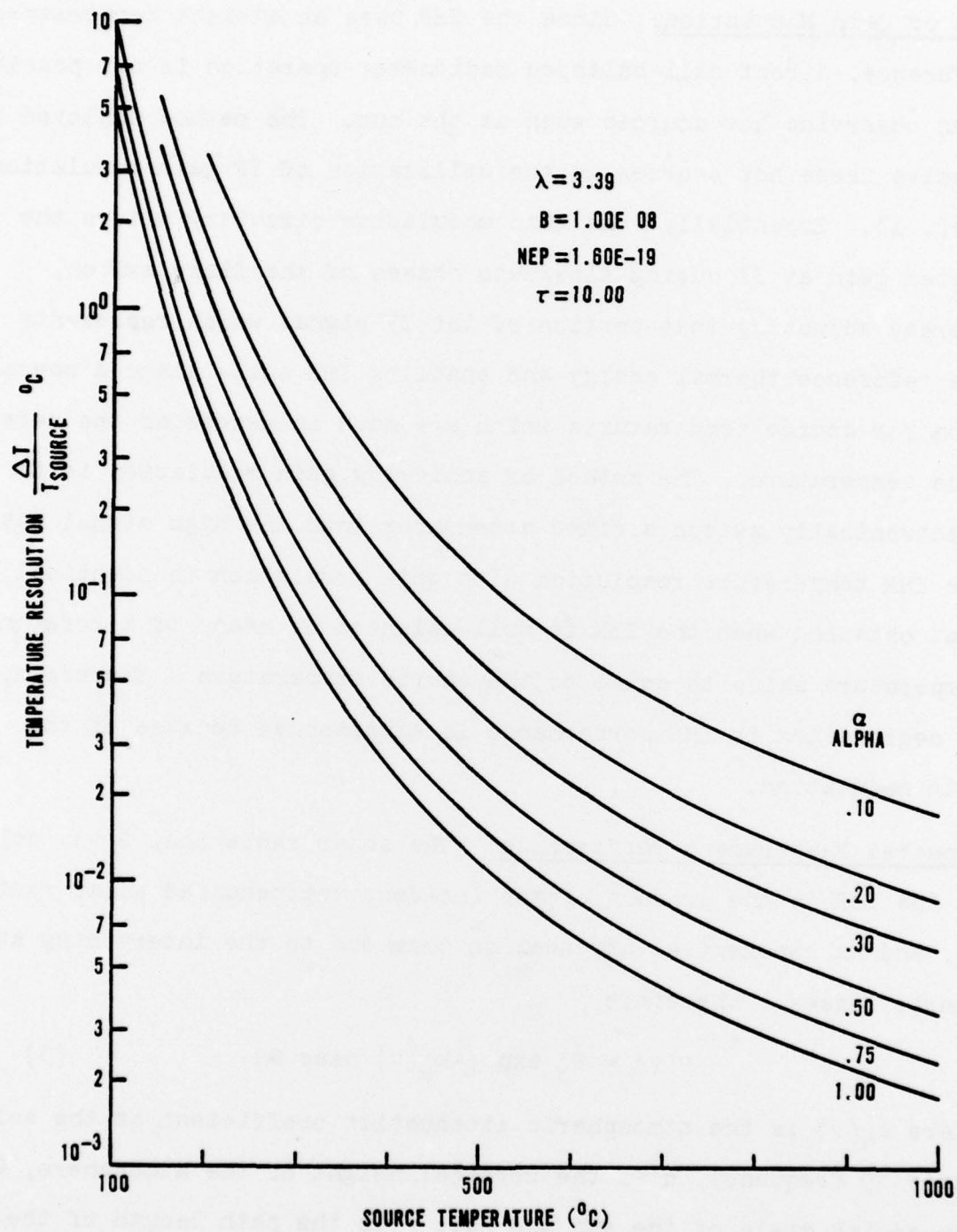$NEP = 1.60E-19$
$\tau = 10.00$

Figure 9.   IHR Temperature Resolution

Use of Gain Modulation: Since the IHR uses an ambient temperature reference, direct null-balanced radiometer operation is not possible when observing hot sources such as the sun. The method employed to resolve these hot sources is the utilization of IF gain modulation (ref. 1). Essentially, the gain modulation circuitry alters the system gain at IF during alternate phases of the Dicke switch, thereby adjusting that portion of the IF signal which represents the reference thermal energy and enabling IHR null-balanced operation for source temperatures which are much in excess of the reference temperature. The method of achieving gain modulation is to electronically switch a fixed attenuator into the high signal path. The IHR temperature resolution with gain modulation is identical to that obtained when the IHR is null-balanced by means of a reference temperature which is equal to the source temperature. Therefore, no degradation in IHR performance is experienced because of the gain modulation.

Expected Measurement Performance: The solar radiation, $P(\nu)$, collected at the IHR is the product of the incident unattenuated solar radiation, P_o, and an exponential attenuation term due to the intervening atmospheric losses. Therefore

$$P(\nu) = P_o \exp\left(-k_\alpha(\nu)\ h\sec\Theta\right) \qquad (3)$$

where $k_\alpha(\nu)$ is the atmospheric attenuation coefficient at the selected laser LO frequency, h is the vertical height of the atmosphere, Θ is the zenith angle of the sun and $h\sec\Theta$ is the path length of the

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sunlight through the atmosphere. The IHR output voltage is proportional to the collected source energy. The slope of the logarithm of $P(\nu)$ plotted against sec θ is $-k_\alpha(\nu)$ h and exp $(-k_\alpha(\nu)$ h) is the total vertical path transmission, α (ref. 1 and 2).

The vertical path atmospheric transmission can be determined by tracking the sun as it traverses the daytime sky from a ground-based or airborne IHR. The measurements can be carried out at different laser local oscillator frequencies, and/or different altitudes.

When observing an extended thermal source of temperature (T_s) which fills the IHR field-of-view, the postdetection signal-to-noise ratio is given (ref. 1) by:

$$SNR = \frac{\eta' \, \alpha \, (B\tau)^{1/2}}{e^{h\nu/kT_s} - 1} \tag{4}$$

where B is the IF bandwidth, τ is the postdetection integration time of an ideal integrator, and k is Boltzmann's constant.

Using equation (3),

$$\alpha = \gamma \frac{S}{N} \tag{5}$$

where γ is a constant for a fixed set of measurement parameters. Differentiating α with respect to S

$$d\alpha = \frac{\gamma}{N} \, dS \tag{6}$$

The minimum detectable signal change occurs when dS = N, therefore the accuracy of the measurement of atmospheric transmission is given by:

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$$\frac{d\alpha}{\alpha} = \frac{1}{SNR} \tag{7}$$

For a typical solar observation, $T_s \approx 5000$ K, B = 100 MHz, $\tau = 10$ sec, and $\eta' = 0.2$, a total atmospheric transmission of $\alpha = 0.5$ from 30 km to sea level during midlatitude summer at $\lambda = 3$, the calculated SNR of a ground-based IHR observing the solar disk at zenith it calculated (equation 4) to be

$$SNR \approx 2000 \tag{8}$$

The expected accuracy of equation (8) of the measurement is:

$$\frac{d\alpha}{\alpha} = \frac{N}{S} \cong 5 \times 10^{-4} \cong 0.05 \text{ percent}$$

Calculations have been carried out to determine the expected transmission values at various altitudes for a number of HF laser lines. The calculations for midlatitude winter model (with no aerosol present) are given in Table 1 (ref. 8). The atmospheric transmissions are given for 3 HF lines; the 2.854 μm transition which is the most strongly absorbed in the atmosphere, the 2.957 μm transition which is the least absorbed in the atmosphere, and the 2.870 μm transition which exhibits an intermediate value of atmospheric absorption. The transmission values have been calculated for the optical path between the edge of the atmosphere and the selected aircraft altitude with the solar viewing angle at a variable parameter.

Calculations were also carried out to determine the obtainable IHR power resolution. The resolution is a function of: (1) the effective system quantum efficiency (η'), and (2) the effective source

Table 1.

Atmospheric Transmission of HF Laser
Midlatitude Winter - No Aerosol
(Θ = Sun's Angle from Zenith)

Altitude (km)	Transmission $\Theta = 80°$	Transmission $\Theta = 70°$	Transmission $\Theta = 60°$	Transmission $\Theta = 50°$	Laser Line (μm)
10	.9225	.9599	.9724	.9785	
9	.8886	.9418	.9598	.9686	2.854 (max abs)
8	.8128	.9001	.9305	.9455	
7	.6478	.8022	.8600	.8893	
6	.3466	.5839	.6921	.7511	
10	.9996	.9998	.9999	.9999	
9	.9993	.9996	.9998	.9998	2.957 (min abs)
8	.9986	.9993	.9995	.9996	
7	.9965	.9982	.9988	.9991	
6	.9907	.9952	.9967	.9975	
10	.9552	.9770	.9842	.9877	
9	.9348	.9664	.9769	.9820	
8	.8984	.9471	.9635	.9717	2.870
7	.8241	.9064	.9350	.9491	
6	.6791	.8216	.8742	.9007	

(calibration) blackbody temperature, and (3) the Bτ product. The smallest calculated change in irradiance which can be measured for a given input radiance is given in Table 2. The system quantum efficiency depends on both the quantum efficiency of the infrared photomixer and the degradation introduced by the front end optical configuration. The PV:InSb photomixer used in the IHR has an effective quantum efficiency of approximately 75 percent. The IHR system loss factor of approximately 3 dB is due to both optic and mixing inefficiency. This yields a system quantum efficiency of 37 percent. As seen from Table 1, the use of a 1900 K blackbody calibration source will yield a resolution between 3 and 4 parts per 1000 as compared to 10 to 13 parts per 1000 for a 1300 K source temperature (this resolution is based on the instrument rms noise).

In comparing the IHR resolution capability with the expected values of transmission (Table 1) it can be seen that most of the HF laser lines can be accurately investigated in the altitude region of interest with the exception of the weakest line at 2.957 and 2.964 microns if a 1900 K blackbody is employed. The measurements of the weaker lines appear to be limited to altitudes below 7 kilometers.

Table 2

Calculated IHR System Resolution

System Quantum Efficiency	IHR System Resolution	
	Blackbody Temp = 1300 K	Blackbody Temp = 1900 K
0.1	0.038	0.011
0.2	0.019	0.0055
0.3	0.013	0.0037
0.4	0.0098	0.0028
0.5	0.0078	0.0022

A 1900 K blackbody calibration source is employed in the IHR to provide improved accuracy and to insure that a calibration reference is available above (T_c = 1900 K) and below (T_c = 290 K) the apparent solar temperature at the IHR.

Conclusions: An infrared heterodyne radiometer has been designed, developed and fabricated for high performance operational capabilities from an airborne platform. The extremely narrow bandwidth (0.0033 cm^{-1}) IHR developed on this contract is an unusual combination of optical, infrared and radio frequency technology.

The instrument has a number of key features which make it particularly advantageous for aircraft applications. These are:

1. Compact packaging of components

2. Ruggedized optical and mechanical mounting

3. High frequency chopping rate (up to 2000 Hz) which reduces the effects of external noise sources

4. Electromagnetic interference suppression filtering

5. Remote control for switching from signal to calibration mode

6. Remote control - selectable calibration source (300 or 1900 K)

7. Variable attenuation mechanism for control of LO power

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During the design and development of the equipment package, consideration was also given to the system modification requirements for operation at other wavelengths. Although the IHR is presently being used for solar and atmospheric transmission measurements, there are a number of other potential applications for this unique instrument. The infrared spectrum is rich in spectral absorption (emission) phenomena which are signatures of a multitude of elements and compounds. The narrow bandwidth IHR offers the potential of spectral overlap with selected signature lines to permit the remote detection and monitoring of various atmospheric constituents.

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